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Full paper

Adaptive dynamic walking of a quadruped robot using a neural system model

HIROSHI KIMURA *, YASUHIRO FUKUOKA and KEN KONAGA

Graduate School of Information Systems, University of Electro-Communications, Chofu-ga-oka 1-5-1, Chofu, Tokyo 182-8585, Japan

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Abstract—We are trying to induce a quadruped robot to walk dynamically on irregular terrain by using a neural system model. In this paper, we integrate several reflexes, such as a stretch reflex, a vestibulospinal reflex and extensor/flexor reflexes, into a central pattern generator (CPG). We try to realize adaptive walking up and down a slope of 12°, walking over an obstacle 3 cm in height, and walking on terrain undulation consisting of bumps 3 cm in height with fixed parameters of CPGs and reflexes. The success in walking on such irregular terrain in spite of stumbling and landing on obstacles shows that the control method using a neural system model proposed in this study has the ability for autonomous adaptation to unknown irregular terrain. In order to clarify the role of a CPG, we investigate the relation between parameters of a CPG and the mechanical system by simulations and experiments. CPGs can generate stable walking suitable for the mechanical system by receiving inhibitory input as sensory feedback and generate adaptive walking on irregular terrain by receiving excitatory input as sensory feedback. MPEG footage of these experiments can be seen at: http://www.kimura.is.uec.ac.jp.

Keywords: Quadruped robot; adaptive dynamic walking; irregular terrain; neural system model; central pattern generator; reflexes via CPG; coupling of dynamics.

1. INTRODUCTION

Many previous studies of legged robots have been performed, and monopod [1], biped [2, 3] and quadruped [4, 5] robots have been studied with regard to dynamic legged locomotion on irregular terrain. Most of these earlier studies employed precise models of a robot and an environment, and involved planning joint trajectories as well as controlling joint motions on the basis of an analysis of the models. If we know all about one particular irregular terrain before an experiment, we can prepare a control program for it. However, when a legged robot moves quickly across a

*To whom correspondence should be addressed. E-mail: hiroshi@kimura.is.uec.ac.jp

variety of locations, a method consisting of modeling, planning and control such as mentioned above is not effective and not adaptable. In order to cope with an infinite variety of terrain irregularity, robots need autonomous adaptation.

On the other hand, animals show marvelous abilities in autonomous adaptation. It is well known that motions of animals are controlled by internal neural systems. As biological studies of motion control progress, it has become generally accepted that an animal's walking is mainly generated at the spinal cord by a combination of a rhythm pattern generator [central pattern generator (CPG)] and reflexes in response to the peripheral stimulus [6]. Much previous research attempted to generate autonomously and emergently adaptable walking using such a biologically inspired control mechanism. It was shown by simulation that stable and adaptive biped walking [7, 8] and stepping [9] could be realized by a global entrainment between a CPG and a musculoskeletal system. It was also shown by simulation that that neural controllers optimized by using an evolutional method [10, 11] could generate walking of a biped or a quadruped. Dynamic walking [12–15] and running [12] of a real robot on flat terrain using CPGs or neural controllers were realized in several earlier studies.

In our previous studies using a quadruped robot, we realized dynamic walking on irregular terrain using a CPG and reflex mechanisms [12, 16]. However, the irregularity of the terrain in those studies was very low. Therefore, in this study we propose a new method for a combination of CPGs and reflexes, and show that reflexes via a CPG are much more effective in adaptive dynamic walking on a terrain with a medium degree of irregularity through experiments using a quadruped robot. In the proposed method, there does not exist adaptation based on trajectory planning commonly used in the conventional robotics. Adaptation to irregular terrain is autonomously generated as a result of interaction of the torque-based system consisting of CPGs and reflexes with the environment.

2. DYNAMIC WALKING USING CPGS

2.1. Quadruped robot

In order to apply the control using a neural system model, we produced a quadruped robot: Patrush-I. Each leg of the robot has three joints, i.e. the hip, knee, and ankle joint, that rotate around the pitch axis. A DC motor and a photo encoder are attached to each hip and knee joint, and the ankle joint is passive. The gear ratio at the hip and knee joints is relatively small: 40 to keep passive mechanical compliance high for adaptive walking. The robot is 36 cm long, 24 cm wide, 33 cm high and 5.2 kg in weight. For a reflex mechanism, a 6-axes force/torque sensor is attached on a lower link beneath the knee joint. A rate-gyro as an angular velocity sensor is mounted on the body as the vestibule. In order to investigate the relation between the parameters of a CPG and the mechanical system by simulations and experiments, we constructed Patrush-II, which has same configuration as Patrush-I

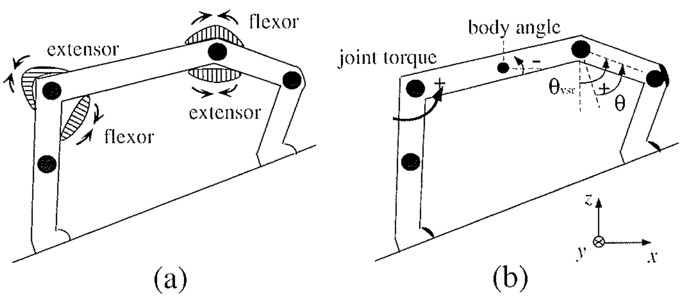


Figure 1. (a) Virtual extensor and flexor muscle on a quadruped robot. (b) Origin and direction of angles and direction of torque.

and can change the length of its legs. The body motion of these robots is constrained on the pitch plane by two poles since the robots have no joints around the roll axis.

In this study, we define the virtual extensor and flexor muscles on a quadruped robot, and origin and direction of joint angle and torque as shown in Fig. 1. In addition, we use such notation as L (left), R (right), F (fore), H (hind), S (hip), x (joint angle), f_x and f_z (force sensor value in x and z direction). For example, LFS means the hip joint of the left foreleg, and LFS.x and LF.fx mean the angle at this joint and force sensor value at this leg.

2.2. *Neural oscillator as a model of the CPG*

By investigation of the motion generation mechanism of a spinal cat, it was found that CPGs are located in the spinal cord and that walking motions are autonomously generated by the neural systems below the brain stem [6]. Several mathematical models of a CPG were proposed, and it was pointed out that a CPG has the capability to generate and modulate walking patterns [17, 18], to be mutually entrained with rhythmic joint motion, and to adapt walking motion to the terrain.

As a model of a CPG, we used a neural oscillator (NO) proposed by Matsuoka [19] and applied to the biped by Taga [8]. This NO has also been applied to the control of rhythmic motion of a robot arm [20, 21]. A single NO consists of two mutually inhibiting neurons (Fig. 2a). Each neuron in this model is represented by the non-linear differential equations:

$$\begin{aligned} \tau \dot{u}_{\{e,f\}i} &= -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} + u_0 \\ &\quad + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_j, \qquad (1) \\ y_{\{e,f\}i} &= \max(0, u_{\{e,f\}i}), \\ \tau' \dot{v}_{\{e,f\}i} &= -v_{\{e,f\}i} + y_{\{e,f\}i}, \end{aligned}$$

where suffix e, f and i mean extensor muscle, flexor muscle and the ith neuron, respectively. u_i is the inner state of a neuron; v_i is a variable representing the degree of the self-inhibition effect of the ith neuron; y_i is the output of the ith neuron; u_0 is

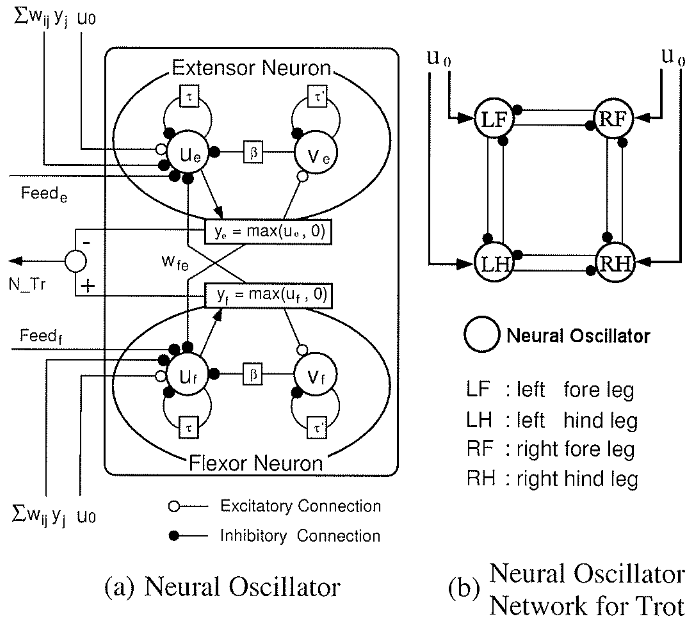


Figure 2. Neural oscillator as a model of a CPG.

an external input with a constant rate; $Feed_i$ is a feedback signal from the robot, i.e. a joint angle, angular velocity, etc.; and β is a constant representing the degree of the self-inhibition influence on the inner state. The quantities τ and τ' are time constants of u_i and v_i; w_{ij} is a connecting weight between the ith and jth neurons. As a result, a NO output torque proportional to the inner state u_e, u_f to a DC motor of a joint:

$$N\_Tr = -p_e y_e + p_f y_f. \tag{2}$$

The positive or negative value of N_Tr corresponds to the activity of the flexor or extensor muscle, respectively.

A stretch reflex in animals acts as feedback loop. The neutral point of this feedback in the upright position of a robot is $\theta = 0$ in Fig. 1b. It is known in biology that there are two different types of stretch reflexes. One is a short-term reflex called the 'phasic stretch reflex' and the other is a long-term reflex called the 'tonic stretch reflex'. When we assume that a tonic stretch reflex occurs on the loop between a CPG and muscles, the joint angle feedback to a CPG used in Taga's simulation [7, 8] based on biological knowledge [22] corresponds to a tonic stretch reflex. We use such joint angle feedback to a CPG (3) in all experiments of this study:

$$Feed_{\text{e-tsr}} = k_{\text{tsr}}\theta, \quad Feed_{\text{f-tsr}} = -k_{\text{tsr}}\theta. \tag{3}$$

We also assume that a phasic stretch reflex occurs on the loop between α motor neurons and muscles locally [16], and mention this reflex in Section 4.1.

By connecting a CPG of a hip joint of each leg, CPGs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between CPGs of legs results in a gait. We used a trot gait, where the diagonal legs are paired and move together, and the two-legs supporting phase is repeated (Fig. 2b).

2.3. Walking on flat terrain using CPGs

In all experiments in this study, only hip joints are controlled by a CPG and knee joints are PD-feedback controlled for simplicity. The desired angle of a knee joint in a supporting phase is 4° and that in a swinging phase is calculated based on the output torque of a CPG, N_Tr, at a hip joint of the same leg by using:

$$\text{desired angle} = 1.7N\_Tr + 0.26. \quad (4)$$

In the experiment using only CPGs and a tonic stretch reflex, where $Feed_{\rm e} = Feed_{\rm e\text{-}tsr}$, $Feed_{\rm f} = Feed_{\rm f\text{-}tsr}$, we confirmed that Patrush-I can walk stably on a flat terrain. This control was almost the same as the one proposed and used in the simulation of biped walking by Taga [8]. Patrush-I walked dynamically with a stride of approximately 25 cm, a walking period of 0.8 s and a speed of 0.6 m/s in this experiment.

3. ENTRAINMENT BETWEEN A CPG AND THE MECHANICAL SYSTEM

In order to clarify the role of a CPG, we investigated the relation between a parameters of a CPG and the mechanical system by simulations and experiments using Patrush-II, and compared CPG walking on flat terrain with passive dynamic walking (PDW) simulated with the physical values of Patrush-II in this section.

3.1. CPG walking and other control methods

In Section 2.3, dynamic stable walking was realized by constructing a stable limit cycle through mutual entrainment between CPGs and the mechanical system. On the other hand, conventional control methods of dynamic walking of a biped and a quadruped can be classified into a 'ZMP-based method' and an 'inverted pendulum model-based method'. In inverted pendulum model-based control, constructing a stable limit cycle on the phase plane utilizing exchange of supporting legs means stabilization of walking [23] and hopping [24]. Therefore, inverted pendulum model-based control has great similarity with the generation and control of walking by CPGs. The typical inverted pendulum model-based walking is PDW where a walking machine with no actuator can walk down a slope dynamically [25].

3.2. Coupling of dynamics of a CPG and the mechanical system

One of the reasons why such a simple CPG described in Section 2.3 can generate dynamic stable walking is that the dynamics of the mechanical system is encoded into parameters of a CPG. Therefore, understanding the relation between the parameters of a CPG and the mechanical system is important in order to the understand roles of a CPG, reduce the time for parameter tuning and help the design of a new walking machine. In previous studies on features of a CPG, Williamson [20] analyzed the stability of a CPG-plant system by using a describing function, and Miyakoshi [26] proposed a method for automatic tuning of the frequency and amplitude parameters for entrainment with an external input. We focus on investigating the relation between parameters of a CPG and the walking mechanism.

3.2.1. Important parameters of a CPG. The properties of a CPG can be expressed by amplitude, period and phase. In (1)–(3), important parameters of a CPG in relation to the mechanical system are τ, u_0, p_e, p_f and k_{tsr}. The amplitude of the CPG output is approximately proportional to u_0 and CPG output is translated into torque at a hip joint by p_e and p_f in (2). Therefore, once proper values of u_0, p_e and p_f are found in simulation 'or experiment', those values will be used as constant values in other simulations or experiments. The period of a CPG is mainly determined by τ and τ'. It was pointed out that the proper value of τ/τ' for stable oscillation is 0.1–0.5 [20]. In this section, we change the value of τ with constant value of τ/τ' and investigate how the walking period is changed. The phase difference between CPGs is kept constant through entrainment on the CPG network (Fig. 2b). We discuss the phase difference between a CPG and the mechanical system in Section 3.3. We make duty factor of walking be 0.5 for simplicity. This means that the duration of a supporting phase is equal to that of a swinging phase and the amplitude of the supporting motion is equal to that of the swinging motion.

3.2.2. CPG period and stability. The walking period is a very important factor since it much influences the stability, maximum speed and energy consumption of dynamic walking [27]. The walking mechanism has its own natural walking period determined mainly by the length of the leg. In this section, we consider the relation between the natural walking period of the mechanism, the free oscillating period of a CPG (T^{o}_{cpg}) determined by τ, and the walking period obtained as a result of entrainment between a CPG and the mechanical system.

Walking motion is constructed by a swinging phase and a supporting phase. We use a single pendulum as a model in the swinging phase and a single inverted pendulum as a model in the supporting phase shown in Fig. 3a in order to analyze the coupling of dynamics of a CPG and the mechanical system. It is well known that the free motion period (natural period) of the pendulum (T^{o}_{sw}) is proportional to the square root of its length. We determine τ as T^{o}_{cpg} is equal to T^{o}_{sw}. When we connect a CPG with the pendulum, the output torque of the CPG drives the pendulum and the CPG receives the angle of the pendulum as a feedback signal expressed by (3). As a result, the CPG and the pendulum are mutually entrained and oscillate with the same period, which becomes smaller than the original period (Fig. 4). This

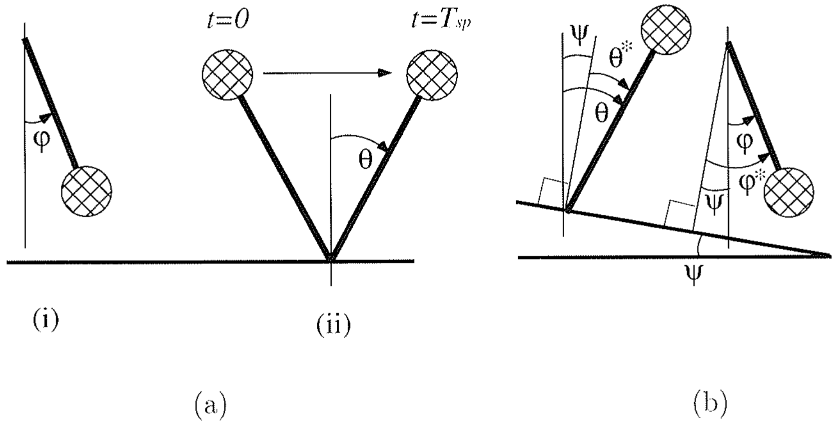


Figure 3. (a) Simple one-link models for a swinging phase (i) and a supporting phase (ii). The length of the pendulum is equal to the distance from the hip joint to the center of mass of a swinging leg. The length of the inverted pendulum is equal to the distance from the floor to the center of mass of a robot. (b) Simple one-link models for a supporting phase and a swinging phase in PDW on a down slope.

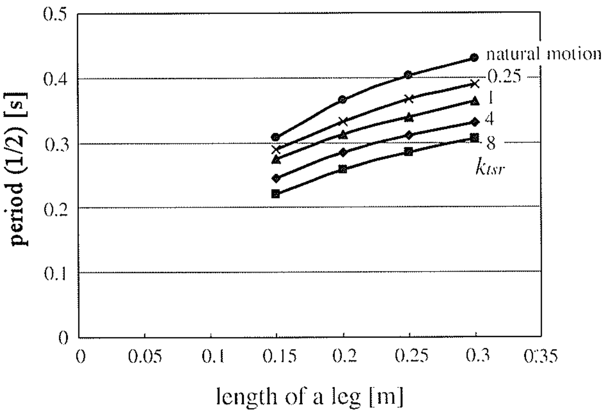


Figure 4. Half of the period of a swinging motion of a leg connected with a CPG. Since the feedback signal from the joint angle gives a CPG an inhibitory effect, the larger value of k_{tsr} makes the period of a CPG smaller.

is because the feedback signal $Feed_{\{e,f\}\cdot tsr}$ gives the CPG an inhibitory effect and consequently makes the period of the CPG be smaller.

In the case of walking, CPGs are entrained with a reciprocating motion where a swinging phase and a supporting phase alternate. The period of a CPG entrained with walking is the CPG walking period (T^{w}_{cpg}), half of which is equal to durations of a swinging phase and a supporting phase. Half of T^{w}_{cpg} obtained through the simulation of walking on a flat terrain are shown in Fig. 5, where T^{o}_{cpg} for each length of a leg is chosen to be equal to T^{o}_{sw}. For comparison, half of T^{o}_{sw}, the duration of free motion of the inverted pendulum as a model of a supporting leg (D^{o}_{sp}), and half of the period of PDW are shown in Fig. 5. Since D^{o}_{sp} depends on not only the

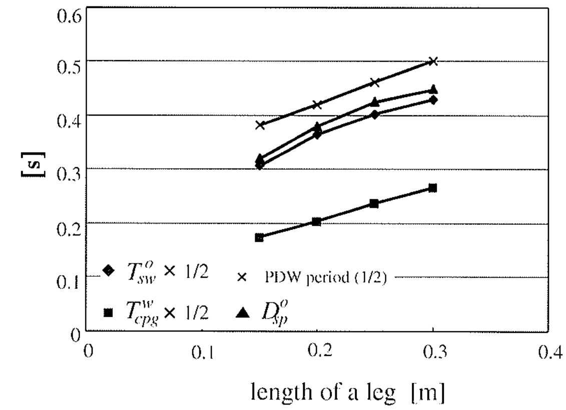


Figure 5. Half of the period of CPG walking $T^{\mathrm{w}}_{\mathrm{cpg}} \times 1/2$, half of the natural period of a swinging leg $T^{\mathrm{o}}_{\mathrm{sw}} \times 1/2$, the duration of the free motion of a supporting leg $D^{\mathrm{o}}_{\mathrm{sp}}$ and half of the period of PDW for various length of a leg. k_{tsr} is 8 rad^{-1}.

length of the leg but also the amplitude of the motion (Appendix A), we used the amplitude of supporting motion in CPG walking for each length of a leg in order to determine $D^{\mathrm{o}}_{\mathrm{sp}}$. In Fig. 5, we can see that $T^{\mathrm{w}}_{\mathrm{cpg}}$ is much smaller that the period shown in Fig. 4 as a result of entrainment with walking motion even though $T^{\mathrm{o}}_{\mathrm{cpg}}$ is equal to $T^{\mathrm{o}}_{\mathrm{sw}}$ in both cases. When the walking period is small, the influence of disturbance in a single supporting phase becomes small and stabilization utilizing phase exchange becomes effective [27]. Therefore, if we choose the same $T^{\mathrm{o}}_{\mathrm{cpg}}$ with $T^{\mathrm{o}}_{\mathrm{sw}}$, the CPG is entrained with both swinging and supporting motions, and stable walking with the smaller period than the original period can be realized as shown in Fig. 5. This is one example of coupling of dynamics of a CPG and the mechanical system.

On the other hand, half of $T^{\mathrm{w}}_{\mathrm{cpg}}$ for various $T^{\mathrm{o}}_{\mathrm{cpg}}$ and the fixed length of a leg are shown in Fig. 6. In Fig. 6, the stable walking was realized while $T^{\mathrm{o}}_{\mathrm{cpg}}$ is close to $T^{\mathrm{o}}_{\mathrm{sw}}$. However, the walking became unstable when half of $T^{\mathrm{o}}_{\mathrm{cpg}}$ is smaller than 0.19 s or larger than 0.52 s, since entrainment between a CPG and the mechanical system was lost. This is an example where the coupling of dynamics was not established.

3.2.3. CPG period and energy consumption. As the second criterion, we consider the energy consumption. In general, when the swinging motion or supporting motion is closer to the free motion of the pendulum or the inverted pendulum in each phase, the motion is more effective. On the other hand, when the swinging or supporting motion differs from the free motion, additional acceleration and deceleration make the motion less effective. As the energy consumption, we use the Joule thermal loss at armatures of DC motors [27]. In Fig. 6 where the energy consumption in walking for various $T^{\mathrm{o}}_{\mathrm{cpg}}$ is shown, we can see that $T^{\mathrm{o}}_{\mathrm{cpg}}$ close to $T^{\mathrm{o}}_{\mathrm{sw}}$ gives the minimum energy consumption. In order to analyze the reason why such minimum energy consumption exists, let us consider the relation of a CPG with free motions in the swinging phase and supporting phase. Half of $T^{\mathrm{o}}_{\mathrm{sw}}$ (the duration of free motion

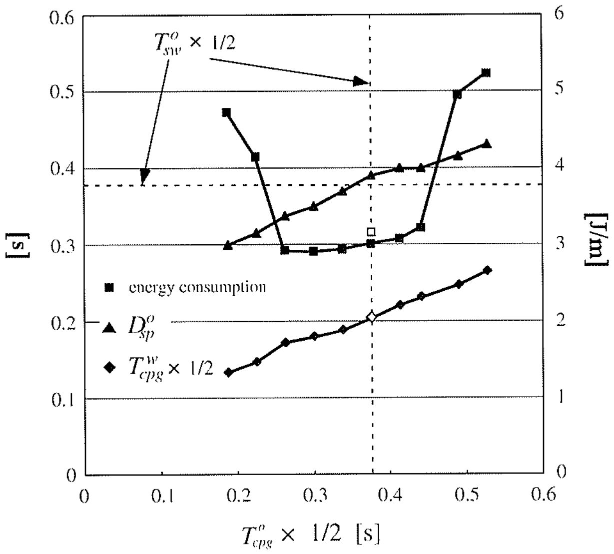


Figure 6. Half of the period of CPG walking $T^{\mathrm{w}}_{\mathrm{cpg}} \times 1/2$, half of the natural period of a swinging leg $T^{\mathrm{o}}_{\mathrm{sw}} \times 1/2$, the duration of the free motion of a supporting leg $D^{\mathrm{o}}_{\mathrm{sp}}$ and energy consumption in CPG walking for half of various free oscillating periods of a CPG $T^{\mathrm{o}}_{\mathrm{cpg}} \times 1/2$. The leg length is 0.2 m and k_{tsr} is 8 rad^{-1}. Solid symbols and blank symbols mean results of simulations and experiments, respectively.

of a swinging leg) and $D^{\mathrm{o}}_{\mathrm{sp}}$ (the duration of free motion of a supporting leg) are also shown in Fig. 6. The energy consumption becomes large as the sum of $T^{\mathrm{o}}_{\mathrm{sw}}/2$ and $D^{\mathrm{o}}_{\mathrm{sp}}$ becomes different from $T^{\mathrm{o}}_{\mathrm{cpg}}$, since unnecessary acceleration and deceleration are required due to the lower entrainment of a CPG with the swinging motion and supporting motion.

3.2.4. Summary. In this subsection, we considered the relation between a CPG and the mechanical system. Matching $T^{\mathrm{o}}_{\mathrm{cpg}}$ with $T^{\mathrm{o}}_{\mathrm{sw}}$ can generate the following superior walking through entrainment between CPGs and swinging/supporting motions.

(i) Stable walking with a smaller period than the original period.
(ii) Efficient walking in terms of energy consumption with less additional acceleration and deceleration.

We realized stable walking in Patrush-II with two different sizes in its leg length, i.e. 0.2 and 0.3 m, by using the same parameters in simulation and confirmed the validity of the above results. The results of experiments using Patrush-II with a leg length of 0.2 m are shown in Fig. 6.

3.3. Phases of a CPG and the mechanical system

There is a similarity between PDW and CPG walking in the sense that dynamic walking is autonomously generated on a link mechanism by an external force

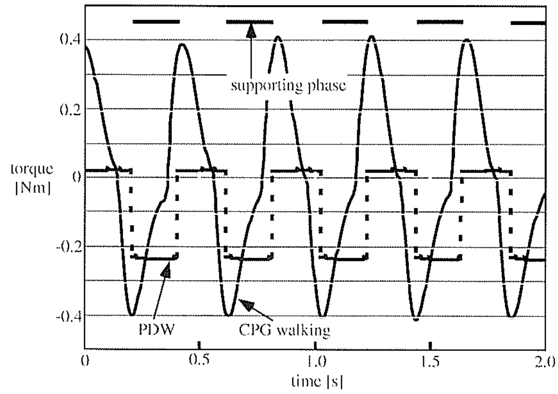


Figure 7. Comparison of CPG torque and additional gravity torque in PDW.

(gravity) or internal torque (CPG torque) as a result of interaction with environment. The result of the comparison of the additional gravity torque in PDW simulation (Appendix B) with the output torque in CPG walking simulation is shown in Fig. 7.

In Fig. 7, additional gravity torque on a leg in PDW is reversed at the switching of the supporting and swinging phases. This shows that walking is exactly passive. On the other hand, switching of the torque of extensor/flexor muscles occurs around 60° in phase before switching the supporting and swinging phases in CPG walking. This switching of the torque of extensor/flexor muscles in the latter period of the supporting and swinging phases is actually observed in animal walking [28]. Through this comparison, we can say that active walking using a CPG is nothing but switching supporting and swinging phases actively by switching of the extensor/flexor torque. This is the reason why active walking using a CPG is much more stable than PDW under errors of initial conditions and disturbances.

Moreover, in dynamic walking on irregular terrain, we can expect that the CPG phase should be adjusted adaptively according to the disturbed motion of the mechanical system for appropriate active switching of the supporting and swinging phases. In the next section, we consider such adjustment of phase of a CPG based on sensory information.

4. REFLEXES VIA A CPG

4.1. Walking on irregular terrain using CPGs and reflexes

Patrush-I failed in walking over an obstacle 3 cm in height and walking up a slope of more than 7° [12, 16] by using only CPGs and a tonic stretch reflex described in Section 2.3. It is well known in biology that adjustment of CPGs and reflexes based on somatic sensation such as contact with the floor and tension at the muscle of supporting legs, and vestibular sensation are very important in adaptive walking [6, 29]. Although it is also well known that CPGs switch sensory information for reflexes and activities of CPGs are modified by sensory

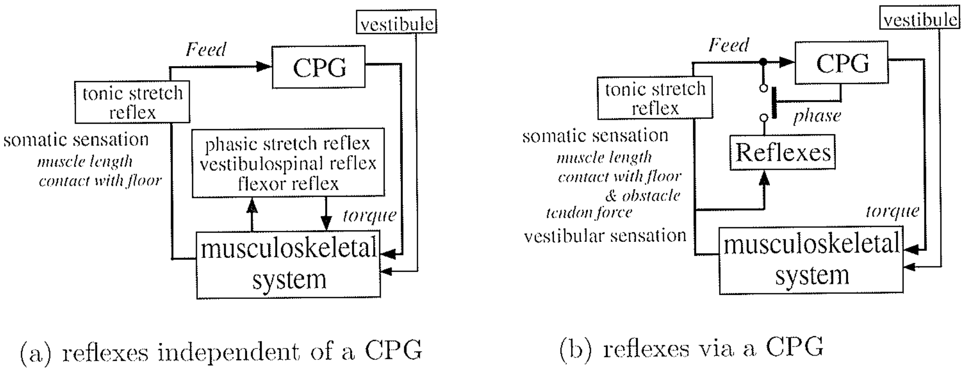


Figure 8. Relation between CPG and reflexes.

feedback [29], the exact mechanism of such interaction between CPGs and reflexes in animals is not clear since the neural system of animals is too complicated. Therefore, we consider the following two types of models for adaptation based on sensory information, discuss which model is better through results of experiments, and propose a physical mechanism of relation between a CPG and reflexes in view of robotics.

(a) A CPG and reflexes independent of a CPG (Fig. 8a).

(b) A CPG and reflexes via a CPG (Fig. 8b).

In model (a), we consider reflexes independent of a CPG, and the sum of the CPG torque and reflexes torque is output to a motor. By using a phasic stretch reflex, a vestibulospinal reflex and a flexor reflex independent of a CPG, we realized walking up and down a slope of 12°, and walking over an obstacle of 3 cm in height [12, 16]. However, the following problems were pointed out:

(i) The delay of joint motion from the phase of a CPG in walking up a slope resulted in slipping and stamping with no progress.

(ii) Since CPGs could not extend the supporting phase corresponding to the extended swinging phase caused by a flexor reflex, it happened that both legs were in the swinging phase at the same time and Patrush-I often fell down forward.

(iii) Sensor-based adjustments to solve such problems increased the number of parameters and made the control system more complex.

In model (b), the reflexes torque is output as part of the CPG torque by feedback of all sensory information to a CPG. Although the response of a reflex in model (b) is delayed due to the time constant in a CPG in comparison with the response in model (a), we can expect adjustment of phases of CPGs based on sensory information. In this section, we consider reflexes via a CPG in response to vestibular sensation, tendon force and contact with floor. Since these reflexes may be confused with such usual reflexes as a vestibulospinal reflex, etc., we call reflexes via a CPG as vestibulospinal 'responses', etc.

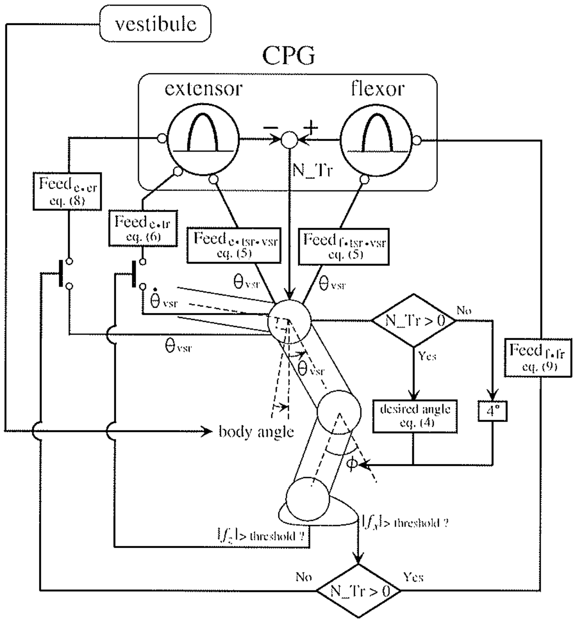


Figure 9. Diagram of actual control of a leg consisting of a CPG and reflexes via a CPG.

A diagram of the actual control of a leg employed in this section is shown in Fig. 9.

4.2. Vestibulospinal response

Since a tonic stretch reflex continues while a muscle is extended, it is appropriate to adjust the activity of antigravity muscles for posture control by a tonic stretch reflex utilizing the body angle detected by vestibule. Therefore, the vestibulospinal response for posture control based on vestibular sensation is via a CPG and expressed by:

$$\begin{aligned} \theta_{\mathrm{vsr}} &= \theta - (\text{body angle}) \quad (\text{rad}), \\ Feed_{\{e,f\}\cdot\mathrm{tsr}\cdot\mathrm{vsr}} &= \pm k_{\mathrm{tsr}} \theta_{\mathrm{vsr}}. \end{aligned} \tag{5}$$

Since the excitatory feedback signal to the extensor neuron of a CPG in walking up a slope makes the active period of the extensor neuron of a CPG longer, the difference between phases of a CPG and joint motion becomes small. In Fig. 10 we can see that the vestibulospinal response via a CPG in walking up a slope made the active period of the extensor neuron of a CPG and the supporting phase of a leg be longer (Fig. 10A) in comparison with those when walking on flat terrain. This means that autonomous adaptability of a CPG solved problem (i) mentioned in Section 4.1.

As a result, Patrush-I succeeded in walking up and down a slope of 12° by using a vestibulospinal response much more stably and smoothly without increasing the number of parameters.

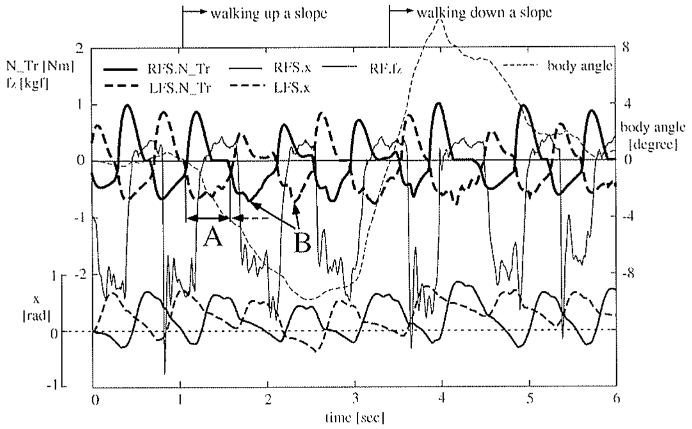


Figure 10. Walking up and down a slope of 12° using feedback (7). $N\_Tr < 0$ means the active period of the extensor neuron of a CPG. $f_z < 0$ means the supporting phase of a leg.

4.3. Tendon response

Pearson *et al.* [30] pointed out that the extensor neuron of a CPG gets an excitatory signal when the tendon organ detects the load to the ankle joint muscle in a supporting phase. We call this as a tendon response, which acts to complement the thrusting force against the reaction force from the floor in the supporting phase.

We use the amount of decrease of $\dot{\theta}$ of a hip joint of a supporting leg for the tendon response instead of the load to the ankle joint muscle. The tendon response via a CPG on a supporting leg is generated by the excitatory feedback signal: $Feed_{\text{e}\cdot\text{tr}}$ to the extensor neuron of a CPG:

$$Feed_{\text{e}\cdot\text{tr}} = \begin{cases} k_{\text{tr}}(\dot{\theta} + 1) & (\dot{\theta} \geqslant -1), \\ 0 & (\dot{\theta} < -1), \end{cases} \tag{6}$$

$$\begin{aligned} Feed_{\text{e}} &= Feed_{\text{e}\cdot\text{tsr}\cdot\text{vsr}} + Feed_{\text{e}\cdot\text{tr}}, \\ Feed_{\text{f}} &= Feed_{\text{f}\cdot\text{tsr}\cdot\text{vsr}}. \end{aligned} \tag{7}$$

By using the sensory feedback to a CPG expressed by (7), Patrush-I succeeded in walking up and down a slope of 12° (Fig. 10). In Fig. 10, the output torque of the tendon response via a CPG appears as bumps on N_Tr while the extensor neuron of a CPG is active ($N\_Tr < 0$) at 1.9 and 2.3 s (Fig. 10B), for example. Although Patrush-I took 4 s to walk up a slope in the experiment without the tendon response in Section 4.2, it took only 2.2 s in Fig. 10. This means that faster walking up a slope was realized by using the tendon response.

4.4. Extensor and flexor responses

It is known in biology that the response to the stimulus on the paw dorsum in walking of a cat depends on which of extensor or flexor muscles are active:

(a) When extensor muscles are active, a leg is strongly extended in order to avoid falling down.

(b) When flexor muscles are active, a leg is flexed in order to escape from the stimulus.

We call (a) and (b) the extensor response and flexor response, respectively, and assume that the phase signal from a CPG switches such responses [29].

For the extensor response, we employ the following excitatory feedback signal $Feed_{\text{e}\cdot\text{er}}$ to the extensor neuron of a CPG when a reaction force larger than the threshold ($f_x > 1.5$ kgf) is detected by the force sensor while the extensor neuron is active ($N\_Tr < 0$):

$$Feed_{\text{e}\cdot\text{er}} = \begin{cases} k_{\text{er}}\theta_{\text{vsr}} & (\theta_{\text{vsr}} \geqslant 0), \\ 0 & (\theta_{\text{vsr}} < 0). \end{cases} \tag{8}$$

For the flexor response, we employ the instant excitatory feedback signal $Feed_{\text{f}\cdot\text{fr}}$ to the flexor neuron of a CPG when a reaction force larger than the threshold ($f_x > 1.5$ kgf) is detected by the force sensor while the flexor neuron is active ($N\_Tr > 0$):

$$Feed_{\text{f}\cdot\text{fr}} = (k_{\text{fr}}/0.12)(0.12 - t), \tag{9}$$

where $t = 0$ s means the instance when a leg stumbles and $Feed_{\text{f}\cdot\text{fr}}$ is active for $t = 0$–0.12 s.

Finally, the feedback signal to a CPG to avoid falling down after stumbling is expressed by:

$$\begin{aligned} Feed_{\text{e}} &= Feed_{\text{e}\cdot\text{tsr}\cdot\text{vsr}} + Feed_{\text{e}\cdot\text{tr}} + Feed_{\text{e}\cdot\text{er}}, \\ Feed_{\text{f}} &= Feed_{\text{f}\cdot\text{tsr}\cdot\text{vsr}} + Feed_{\text{f}\cdot\text{fr}}. \end{aligned} \tag{10}$$

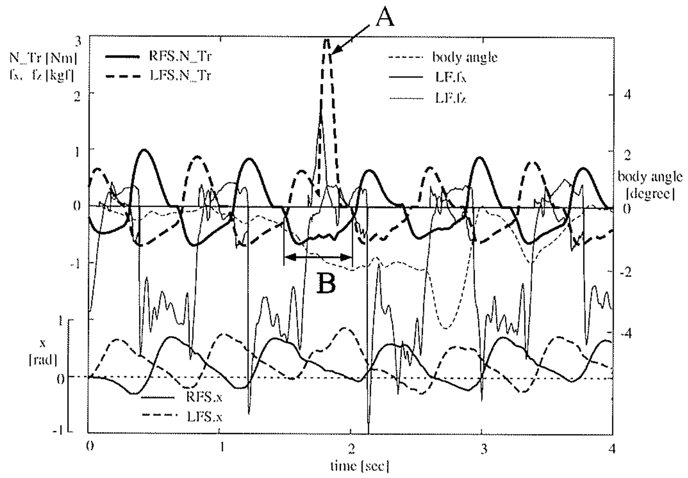


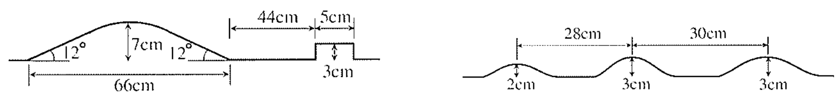
Figure 11. Avoidance of falling down after stumbling on an obstacle by using a flexor response.

In Fig. 11, the left foreleg stumbled on an obstacle at 1.7 s and the neuron torque of the left foreleg (LFS.N_Tr) was instantly increased by the flexor response (Fig. 11A). This flexor response made the active period of the flexor neuron of the left foreleg much longer (1.4–2.0 s). Autonomous adaptability of a CPG made the active period of the extensor neuron of the right foreleg be correspondingly longer (Fig. 11B) in order to prevent Patrush-I from falling down by solving problem (ii) in Section 4.1.

4.5. Adaptation to terrain with a medium degree of irregularity

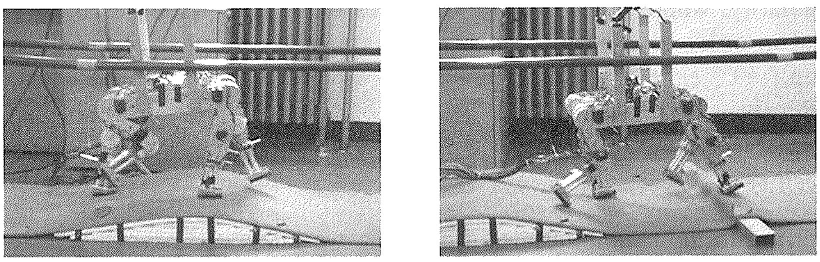
We tried to realize dynamic walking on terrain with medium degree of irregularity, where a slope, a small obstacle and undulations continue in series (Fig. 12). Photos of walking on such irregular terrain are shown in Figs 13 and 14.

The parameters of the CPG and reflexes used in experiments are shown in Table 1. CPG parameters were determined based on the analysis described in Section 3.



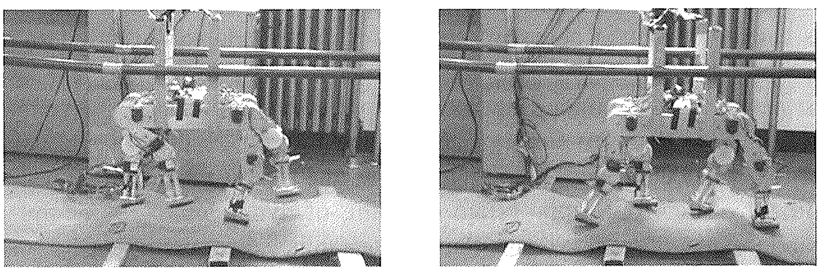
(a) (b)

Figure 12. Terrain with a medium degree of irregularity.



(a) (b)

Figure 13. Photographs of walking up and down a slope (a), and walking over an obstacle (b).



(a) (b)

Figure 14. Photographs of walking on terrain undulations.

Table 1.
Value of parameters used in experiments

Parameters	Value
u_{0i}	8.5
τ	0.05
τ'	0.6
β	1.5
w_{fe}	−2.0
w_{ij}	±1.0
p_f, p_e (Nm)	0.075, 0.12
k_{tsr} (1/rad)	8.0
k_{tr} (s/rad)	5.8
k_{er} (1/rad)	5.0
k_{fr}	50.0

Reflex parameters were determined heuristically through experiments, since the relation between reflexes parameters via a CPG and the mechanical system has not yet been investigated.

By realization of such adaptive walking using the control method expressed by (1) and (10) with fixed values of all parameters, we showed that the control method proposed in this section (Fig. 9) has ability for adaptation to an unknown terrain with medium degree of irregularity. For walking on terrain with a higher degree of irregularity, where holes or large obstacles exist, adaptation based on vision is essential in order to control the exact position of landing or change the walking direction.

5. CONCLUSION

By referring to the neural system of animals, we integrated several reflexes, such as a stretch reflex, a vestibulospinal reflex and extensor/flexor reflexes, into a CPG. In the case of reflexes via a CPG, it was shown by experiments using Patrush-I that the active periods of the flexor and extensor neurons of CPGs could be appropriately adjusted autonomously by the ability of CPGs for entrainment, while reflexes via a CPG output necessary torque for instant adaptation based on sensory information.

In the neural system model method, only relations among CPGs, reflexes and the mechanical system are simply defined, and motion generation and adaptation is emergently induced by the dynamics in the neuro-mechanical system and environment. Therefore, appropriate coupling of dynamics of the neural system model and the mechanical system should be established for emergence of desirable motion. The analysis of the relation between parameters of a CPG and the mechanical system in this study is the first step for establishing such coupling of dynamics.

The neural oscillator as a model of a CPG outputs both amplitude and phase information as a feedforward signal. The CPG receives inhibitory input from the joint angle as a sensory feedback signal, shortens its own period through entrainment with the mechanical system and adaptively generates stable walking suitable for the mechanical system. The CPG receives excitatory input from reflexes as a sensory feedback signal, enables the mechanical system to adapt to irregular terrain, extends its own period in response to any delay of motion of the mechanical system and adjusts the phase difference between CPGs. Although another model of a CPG giving only phase information as a clock was proposed [15], this study showed that amplitude information of a CPG is also useful since it enables integration of reflexes into a CPG, and simultaneous adaptation of amplitude and phase.

Three-dimensional dynamic walking on two-dimensional irregular terrain is one of the next challenges of this study. Learning at the cerebellum for adaptation and learning at the basal ganglia and the cortex for adjustment based on vision are left unsolved.

Acknowledgements

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REFERENCES

1. J. K. Hodgins and M. H. Raibert, Adjusting step length for rough terrain locomotion, *IEEE Trans. Robotics Automat.* **7**, 289–298 (1991).
2. J. Yamaguchi, A. Takanishi and I. Kato, Development of a biped walking robot adapting to a horizontally uneven surface, in: *Proc. Int. Conf. on Intelligent Robots and Systems*, pp. 1030–1037 (1994).
3. S. Kajita and K. Tani, Adaptive gait control of a biped robot based on realtime sensing of the ground, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 570–577 (1996).
4. K. Yoneda, H. Iiyama and S. Hirose, Sky-hook suspension control of a quadruped walking vehicle, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 999–1004 (1994).
5. M. Buehler, R. Battaglia, A. Cocosco, G. Hawker, J. Sarkis and K. Yamazaki, Scout: a simple quadruped that walks, climbs and runs, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 1707–1712 (1998).
6. S. Grillner, Control of locomotion in bipeds, tetrapods and fish, in: *Handbook of Physiology II*, pp. 1179–1236. American Physiol. Society, Bethesda, MD (1981).
7. G. Taga, Y. Yamaguchi and H. Shimizu, Self-organized control of bipedal locomotion by neural oscillators, *Biol. Cybernet.* **65**, 147–159 (1991).
8. G. Taga, A model of the neuro-musculo-skeletal system for human locomotion II. Real-time adaptability under various constraints, *Biol. Cybernet.* **73**, 113–121 (1995).
9. S. Miyakoshi, G. Taga, Y. Kuniyoshi and A. Nagakubo, Three dimensional bipedal stepping motion using neural oscillators — towards humanoid motion in the real world, in: *Proc. Int. Conf. on Intelligent Robots and Systems*, pp. 84–89 (1998).
10. N. Yamazaki, K. Hase, N. Ogihara and N. Hayamizu, Biomechanical analysis of the development of human bipedal walking by a neuro-musculo-skeletal model, *Folia Primatol.* **66** 253–271 (1996).

11. A. J. Ijspeert, J. Hallman and D. Willshaw, From lampreys to salamanders: evolving neural controllers for swimming and walking, in: *Proc. 5th Society for Adaptive Behavior*, pp. 390–399 (1998).
12. H. Kimura, S. Akiyama and K. Sakurama, Realization of dynamic walking and running of the quadruped using neural oscillator, *Auton. Robots* **7**, 247–258 (1999).
13. W. Ilg, J. Albiez, H. Jedele, K. Berns and R. Dillmann, Adaptive periodic movement control for the four legged walking machine BISAM, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 2354–2359 (1999).
14. M. A. Lewis, R. Etienne-Cummings, A. H. Cohen and M. Hartmann, Toward biomorphic control using a custom aVLSI CPG chips, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 1289–1295 (2000).
15. K. Tsujita, A. Onat, K. Tsuchiya, *et al.*, Autonomous decentralized control of a quadruped robot locomotion using oscillators, in: *Proc. 5th Int. Symp. on A-Life and Robotics*, pp. 703–710 (2000).
16. H. Kimura, Y. Fukuoka and H. Nakamura, Biologically inspired adaptive dynamic walking of the quadruped on irregular terrain, in: *Robotics Research 9*, J. M. Hollerbach and D. E. Koditschek (Eds), pp. 329–336. Springer, London (2000).
17. H. Yuasa and M. Ito, Coordination of many oscillators and generation of locomotory patterns, *Biol. Cybernet.* **63**, 177–184 (1990).
18. J. J. Collins and I. N. Stewart, Coupled nonlinear oscillators and the symmetries of animal gaits, *J. Nonlinear Sci.* **3**, 349–392 (1993).
19. K. Matsuoka, Mechanisms of frequency and pattern control in the neural rhythm generators, *Biol. Cybernet.* **56**, 345–353 (1987).
20. M. M. Williamson, Designing rhythmic motions using neural oscillators, in: *Proc. Int. Conf. on Intelligent Robots and Systems*, pp. 494–500 (1999).
21. S. Kotosaka and S. Schall, Synchronized robot drumming by neural oscillators, in: *Proc. Int. Conf. on Adaptive Motion of Animals and Machines*, TuA-II-4 (2000).
22. O. Andersson and S. Grillner, Peripheral control of the cat's step cycle. II Entrainment of the central pattern generators for locomotion by sinusoidal hip movements during fictive locomotion, *Acta Physiol. Scand.* **118**, 229–239 (1983).
23. H. Miura and I. Shimoyama, Dynamical walk of biped locomotion, *Int. J. Robotics Res.* **3**, 60–74 (1984).
24. M. H. Raibert, *Legged Robots that Balance*. MIT Press, Cambridge, MA (1986).
25. T. McGeer, Passive dynamic walking, *Int. J. Robotics Res.* **9**, 62–82 (1990).
26. S. Miyakoshi, G. Taga and Y. Kuniyoshi, A self tuning mechanism for the parameters of a neural oscillator, in: *Proc. RSJ Robotics Symp.*, pp. 301–306 (2000).
27. H. Kimura, I. Shimoyama and H. Miura, Dynamics in the dynamic walk of a quadruped robot, *Advanced Robotics* **4**, 283–301 (1990).
28. K. Pearson, The control of walking, *Sci. Am.* **234**, 72–87 (1976).
29. A. H. Cohen and D. L. Boothe, Sensorimotor interactions during locomotion: principles derived from biological systems, *Auton. Robots* **7**, 239–245 (1999).
30. G. Hiebert, M. Gorassini, W. Jiang, A. Prochazka and K. Pearson, Corrective responses to loss of ground support during walking II, *J. Neurophysiol.* **71**, 611–622 (1994).

APPENDIX A: ANALYSIS OF FREE MOTION IN A SUPPORTING PHASE

We obtain the relation between amplitude and duration of free motion in a supporting phase by using an inverted pendulum model (Fig. 3a). Let T be the

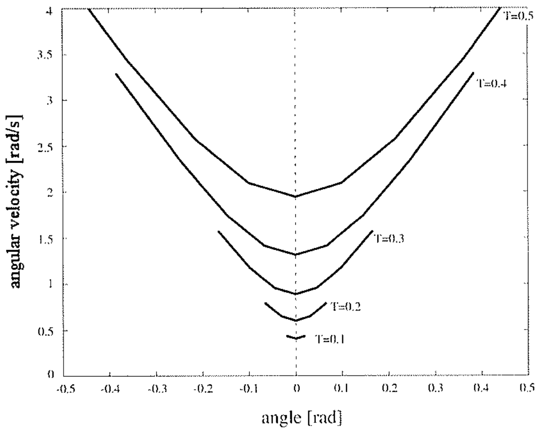


Figure A1. The free motion of an inverted pendulum as a model of a supporting leg on a phase plane.

duration of a supporting phase. The equation of motion and switching conditions on instant exchanging of supporting legs [23] are expressed as:

$$I_\theta \ddot{\theta} = M_\theta g l_\theta \theta, \tag{A.1}$$

$$\theta(T) = -\theta(0), \tag{A.2}$$

$$\dot{\theta}(T) = \dot{\theta}(0), \tag{A.3}$$

where I_θ, M_θ and l_θ are inertia moment, mass and length of the inverted pendulum, respectively. The calculation results of (A.1) with conditions (A.2) and (A.3) for various values of T are shown in Fig. A1, where physical values of Patrush-II ($M_\theta = 0.29$ kg, $l_\theta = 0.16$ m) are used. We can see that the smaller amplitude of link motion makes the duration of the supporting phase shorter.

APPENDIX B: ADDITIONAL GRAVITY TORQUE IN PDW

In order to calculate additional gravity torque in PDW, we use models of an inverted pendulum in a supporting phase and a pendulum in a swinging phase (Fig. 3b). Gravity torques induced on a leg in a supporting phase and a swinging phase are expressed as $\tau_\theta = M_\theta g l_\theta \sin\theta$ and $\tau_\varphi = -M_\varphi g l_\varphi \sin\varphi$, respectively. Those are transformed to the following equations by using θ^* and φ^* (Fig. 3b), where $\cos\psi \simeq 1$:

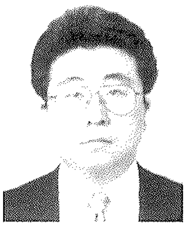
$$\tau_\theta = M_\theta g l_\theta \{\cos\theta^* \sin\psi + \sin\theta^*\}, \tag{B.1}$$

$$\tau_\varphi = M_\varphi g l_\varphi \{\cos\varphi^* \sin\psi - \sin\varphi^*\}. \tag{B.2}$$

In (B.1) and (B.2), the second terms mean gravity torque induced in motion around the normal direction of the floor and also appear in walking on a flat floor. Therefore, the first terms indicate additional gravity torque induced on a leg by the slope with inclination ψ and can be compared with the CPG torque when walking on a flat floor.

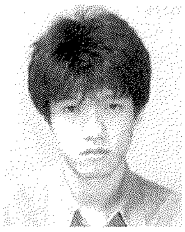
In Fig. 7, we chose the free oscillating period of a CPG so that the period of CPG walking was equal to that of PDW. Since the direction of torque on a supporting leg in Fig. 3b was opposite to that in Fig. 1b, the gravity torque on a supporting leg in Fig. 7 was negated.

ABOUT THE AUTHORS



Hiroshi Kimura was born in Hiroshima, Japan in 1961. He received the BE, ME and DrEng degrees in Mechanical Engineering from the University of Tokyo in 1983, 1985 and 1988, respectively. At present, he is an Associate Professor of the Graduate School of Information Systems at the University of Electro-Communications. His research interests are the dynamics of machinery and intelligence.

Yasuhiro Fukuoka was born in Okayama, Japan in 1974. He received the BE degree in Electrical Engineering from Ehime University in 1996 and the ME degree in Information Systems from the University of Electro-Communications in 2000. At present, he is a Doctoral course student of the Graduate School of Information Systems at the University of Electro-Communications. His research interests are the dynamics of machinery.



Ken Konaga was born in Kyoto, Japan in 1975. He received the BE degree in Electronic Engineering from Tokyo University of Agriculture & Technology in 1999 and the ME degree in Information Systems from the University of Elector-Communications in 2001. At present, he is a Doctoral course student of the Graduate School of Information Systems at the University of Electro-Communications. His research interests are the dynamics of machinery.